PROSPECTS FOR AN ADVANCED COMPTON TELESCOPE WITH HIGH RESOLUTION XENON TIME PROJECTION CHAMBERS

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- Science and Sensitivity Requirements for a Next Generation ACT
- The Time Projection Chamber Approach to a High Resolution ACT
- The Liquid Xenon Time Projection Chamber Development at Columbia: from Proof-of-Principle to Balloon-Borne Compton Telescope (LXeGRIT)
- The Xenon Gas Time Projection Chamber Development at Columbia: an approach to Improve Energy Resolution and Tracking Capability
- Monte Carlo Studies of a High and Low Density Xe-ACT Concept
- The Future: Very Promising with Enhanced Technology Development

Reasons for a Next Generation Compton Telescope for MeV Astrophysics

The Science is Compelling:

The impact of nuclear astrophysics on so many other areas of astronomy and physics is unique

The Field is Largely Unexplored:

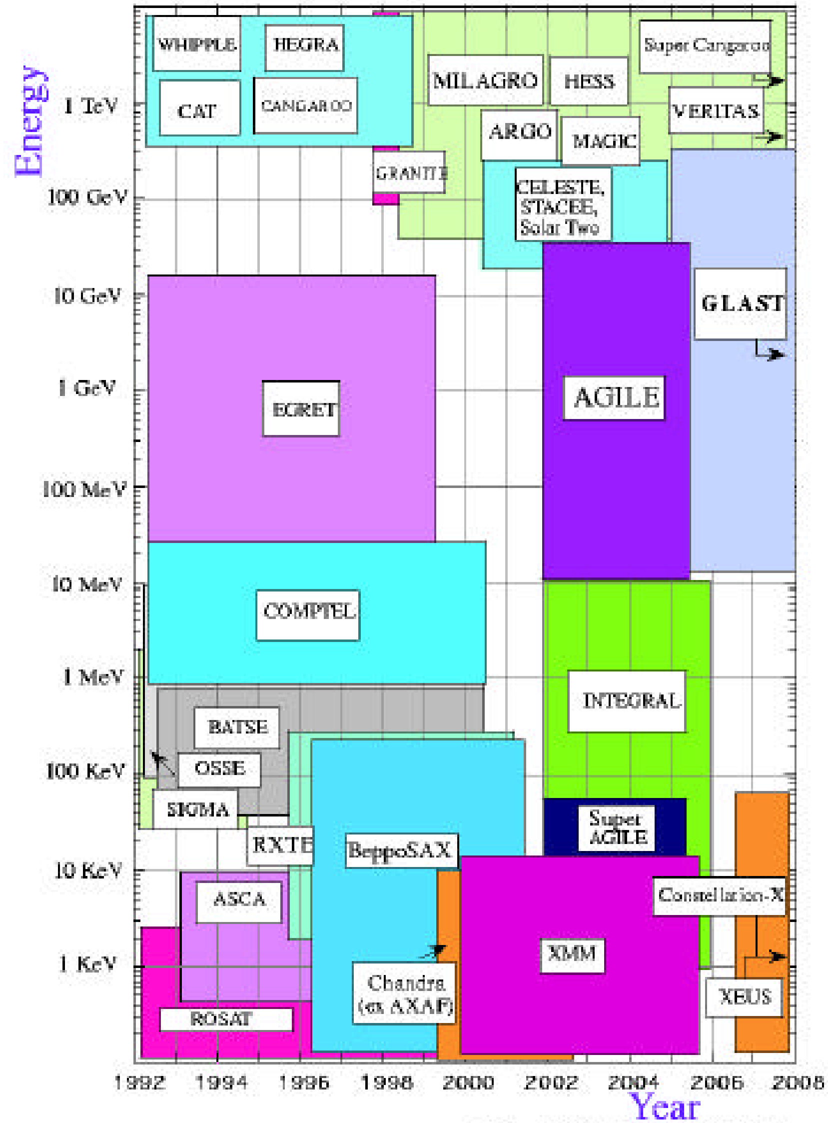
COMPTEL is the first and only Instrument for the exploration of an Energy Band so Rich

The Time is Right:

Progress in Detector Technologies and Methods is such that a 2nd Generation instrument is feasible

The Community is Ready:

As noted in the *Recommended Priorities for NASA's Gamma-Ray Astronomy Program 1999-2013 (GRAPWG)* Nuclear Astrophysics is the highest priority science topic for a mission beyond GLAST, Con-X HXT and SWIFT



Existing and Planned Instruments for High Energy Astronomy. Not shown are HETE-2 and SWIFT

Science Objectives of a Next Generation Nuclear Line Mission

- What is the total Galactic Star Formation Rate today? How is (massive) star formation distributed around the disk? How uniform is SN nucleosynthesis in the Galaxy? (^{26}Al, ^{60}Fe and e^+-e^- annihilation)
- What is the Galactic rate of SN of various types? (^{26}Al, ^{60}Fe, ^{44}Ti, e^+)
- What is the nature of the nuclear burning in Type Ia SN? (^{56}Ni, ^{56}Co). How do the explosions vary with metallicity?(^{57}Co). How/where is the nuclear flame ignited?(^{60}Fe)
- What are the progenitors of Galactic Type Ia SN? (^{60}Fe, e^+). How homogeneous are Galactic SN Ia? (^{60}Fe, ^{44}Ti,e^+). How does iron nucleosynthesis vary with redshift? (^{56}Co)
- Where is the mass-cut in core-collapse SN explosions? (^{56}Co, ^{57}Co, ^{44}Ti). What is the black hole birthrate in the Galaxy (^{44}Ti)?
- What are the structures and mass-loss rates of massive stars? (^{26}Al)
- What is the nature of the thermonuclear runaway and dynamics of classical novae? (^{22}Na, ^{26}Al, ^{7}Be, e^+)
- What are the spectra, intensities and composition of low-energy (10 – 100 MeV) cosmic rays? Do they dominate heating of certain phases of the ISM? (^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg)
- What is the distribution of positrons in the Galaxy? Is there a galactic “fountain” of positrons near the Galactic Center? If so, what is its source?

Cosmic Gamma-Ray Lines (Energy Range: $\sim$ 0.1 – 7 MeV)

Radioactive decay:

- $\tau < 1$ yr: ^{56}Ni/^{56}Co, ^{59}Fe, ^{7}Be
- $\tau < 10$ yr: ^{57}Co, ^{22}Na, ^{60}Co
- $\tau < 100$ yr: ^{44}Ti
- $\tau \gg 100$ yr: ^{26}Al, ^{60}Fe

Nuclear interactions:

nuclear deexcitation lines from interactions of accelerated particles (cosmic rays, in solar flares, around compact objects) with ambient matter: ^{12}C, ^{16}O, ^{20}Ne, ^{22}Ne, ^{24}Mg, ^{28}Si, . . .

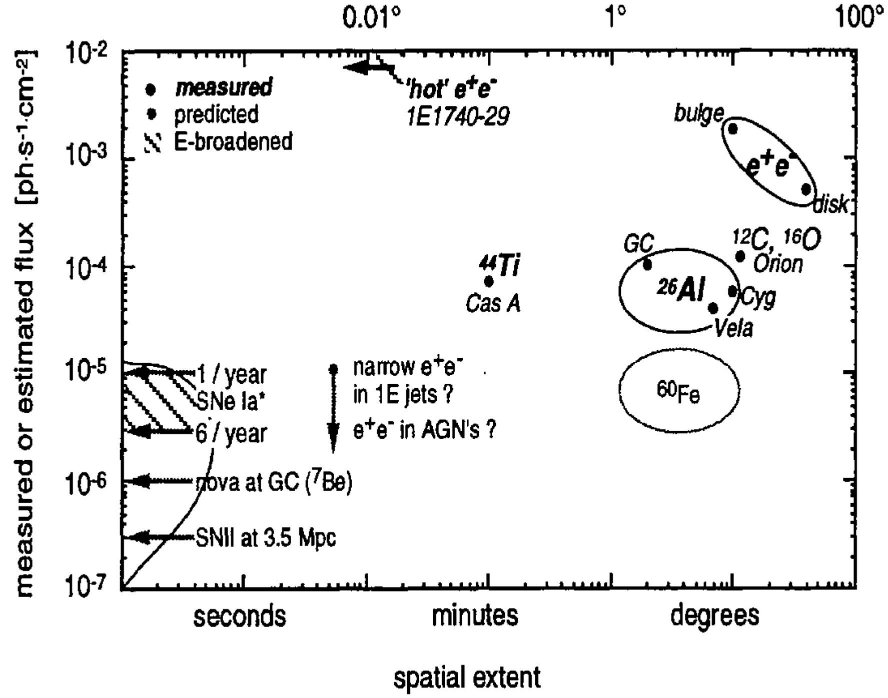
Neutron capture:

mainly ^{1}H(n,γ)^{2}H (solar flares)

e^+e^- annihilation:

narrow line after deceleration of e^+, broad emission from hot plasmas

Spatial extent and flux levels of γ-ray line emission



(von Ballmoos 1995)

Continuum Sources at Medium Gamma-Ray Energies

Transient / time variable sources:

- Pulsars (Crab, Vela, . . .) - pulsed and non-pulsed emission
- X-ray binaries, black-hole candidates (Cyg X-1, 1E1740-294, . . .)
- Active galactic nuclei (3C273, PKS0528+134, . . .)
- Gamma-ray bursts

Time constant sources:

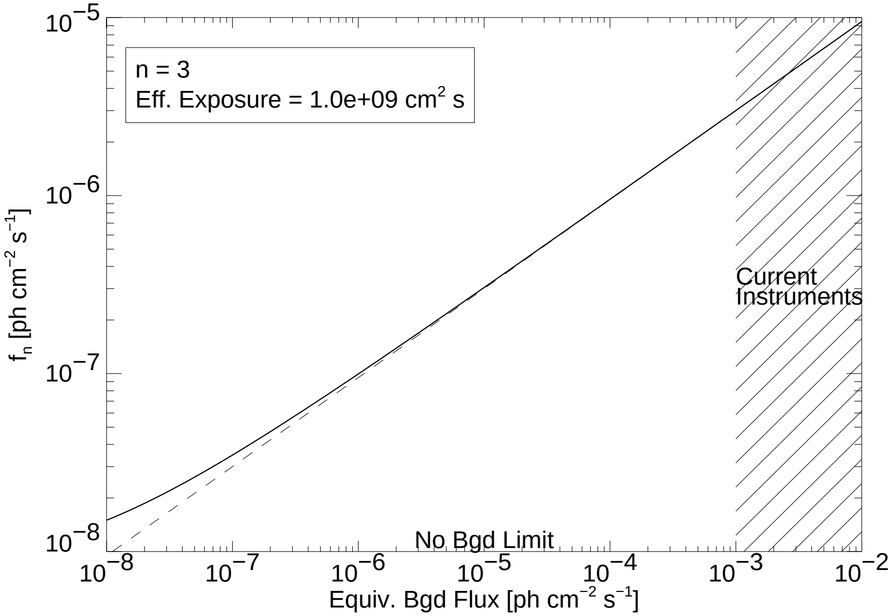
- Galactic diffuse emission (cosmic rays: e^- bremsstrahlung, inverse Compton effect, π^0 decay)
- Cosmic diffuse gamma-ray background (from AGNs, SNIa?)
- supernova remnants

Observational Requirements for a Next Generation Compton Telescope

Goal: $10^{-7}\gamma\cdot$ cm$^{-2}\cdot$ s^{-1} $(3\ \sigma)$ narrow line sensitivity in 10^6 s. Sensitivity should decrease only by a small factor for broad lines and diffuse emission.

Source detection limit: ($n\sigma$ significance)

$$f_n = \frac{n^2}{2A_{\rm eff}\,t_{\rm obs}}\left[1+\sqrt{1+\frac{4\alpha\, f_b A_{\rm eff} t_{\rm obs}}{n^2}}\right] \approx n\sqrt{\frac{\alpha\, f_b}{A_{\rm eff}\,t_{\rm obs}}}$$



State-of-the-art:

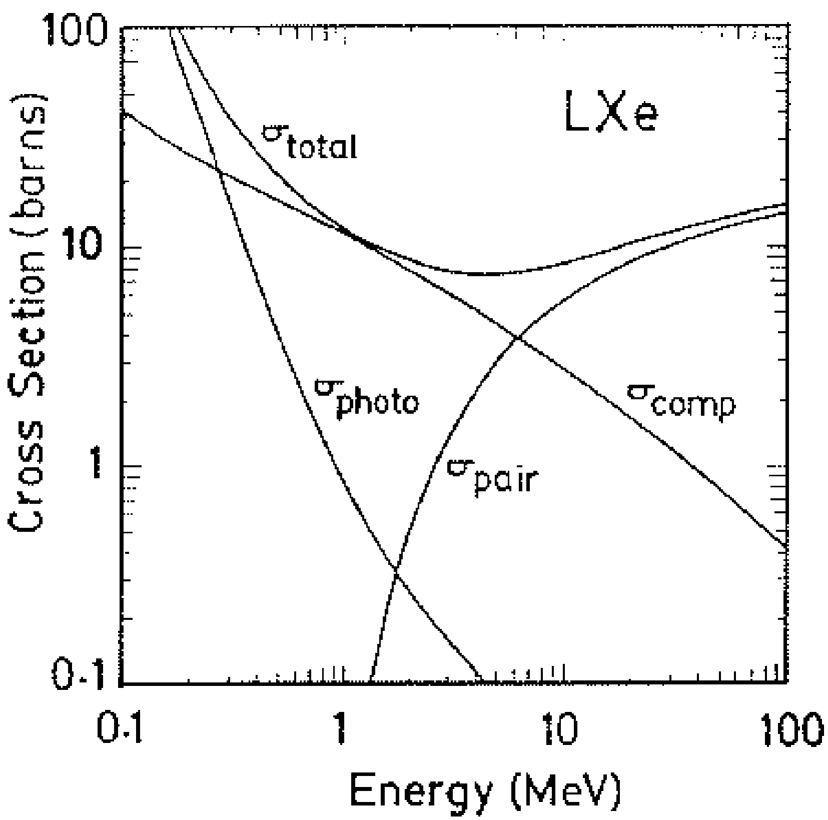
- COMPTEL's 5 yrs effective exposure $\sim 7\times 10^7$ cm$^2\cdot$s^{-1} at 1.8 MeV $\rightarrow$ to gain a factor of 150 at same S/N one needs a factor 150^2 increase in exposure $\rightarrow \sim 1.6\cdot 10^{12}$ cm$^2\cdot$s^{-1} $\rightarrow$ 5 yrs observing time for 1 m^2 effective area!

Future Instruments Require:

- An increase in effective area by a factor of $\sim$500 over COMPTEL ($\sim$5 cm^2 @ 1.8 MeV after selections) $\rightarrow$ large increase in efficiency
- A dramatic improvement in background reduction by a factor $\geq$100 over COMPTEL
- a very large FOV (1/4 - 1/2 of the Sky) to increase the observing time for many sources simultaneously

The Compton Telescope is the Most Promising Concept for MeV Gamma-Ray Astronomy

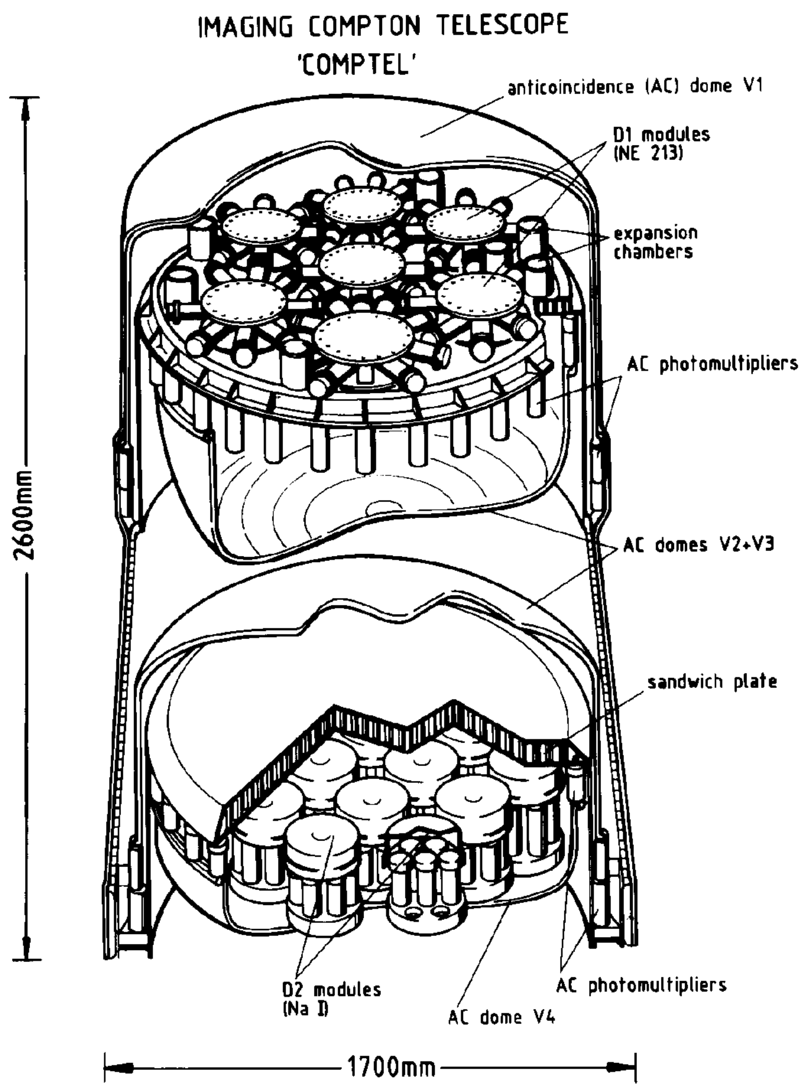
Cross Sections



Technologies under Investigation

- Liquid and gas xenon TPC
- Si strip detectors
- Ge strip detectors
- CZT and CdTe strip detectors

Success of First C.T. in Space: COMPTEL



Liquid Xenon Properties

- High density and atomic number $\rightarrow$ High stopping power

Material	Density [g/cm^3]	Atomic number	Attenuation length @ 1 MeV [cm]
LXe	3.06	54	5.6
Si	2.33	14	6.7
Ge	5.36	32	3.3

- Small W-value for ionization and scintillation
  $\rightarrow$ High electron and photon yields

Material	W-value [eV]
LXe	15.6
Other noble gases/liquids	> 20
Si	3.6
Ge	2.8

- Small Fano factor ($F = 0.041$)
  $\rightarrow$ Excellent energy resolution *expected*

$$\Delta E/E \propto \sqrt{W F/E_\gamma} \qquad W F_{\mathrm{LXe}} = 0.64\ \mathrm{eV} \approx W F_{\mathrm{Ge}}$$

- High electron mobility $\rightarrow$ Fast detector response
  $\vec{v} = \mu \vec{E}$

Material	Electron mobility μ_e [cm^2 V^{-1} s^{-1}]	Mobility of holes (ions) [cm^2 V^{-1} s^{-1}]
LXe	2000	Ion mobility $\mu_i \ll \mu_e$
Si	1900 (21000 @ 77 K)	480 (11000 @ 77 K)
Ge	3800 (40000 @ 77 K)	1800 (40000 @ 77 K)

- Short radiation length and small diffusion constant
  $\rightarrow$ Good spatial resolution for a TPC

Material	Radiation length X_0 [cm]
LXe	2.8
Si	9.4
Ge	2.3

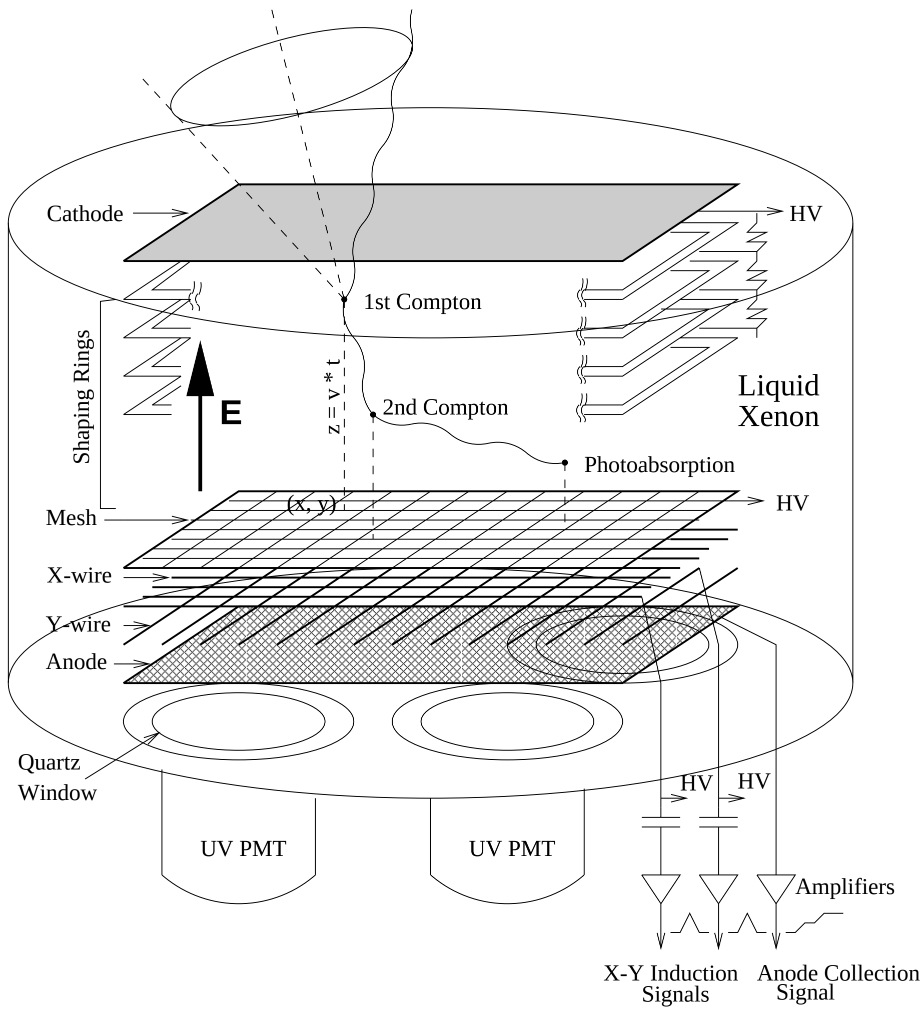
The Liquid Xenon Time Projection Chamber for Compton Imaging of MeV Gamma-Rays

- A homogeneous, self-triggered detector which combines high detection efficiency and low background with calorimetry and tracking capability

- Xe ionization and scintillation signals used to measure energy and 3D spatial information for each gamma-ray interaction in the sensitive volume

- Signal sensing structure optimized for the detection of the localized charge clouds produced in the liquid by low energy Compton electrons and photoelectrons associated with MeV gamma-ray interactions.

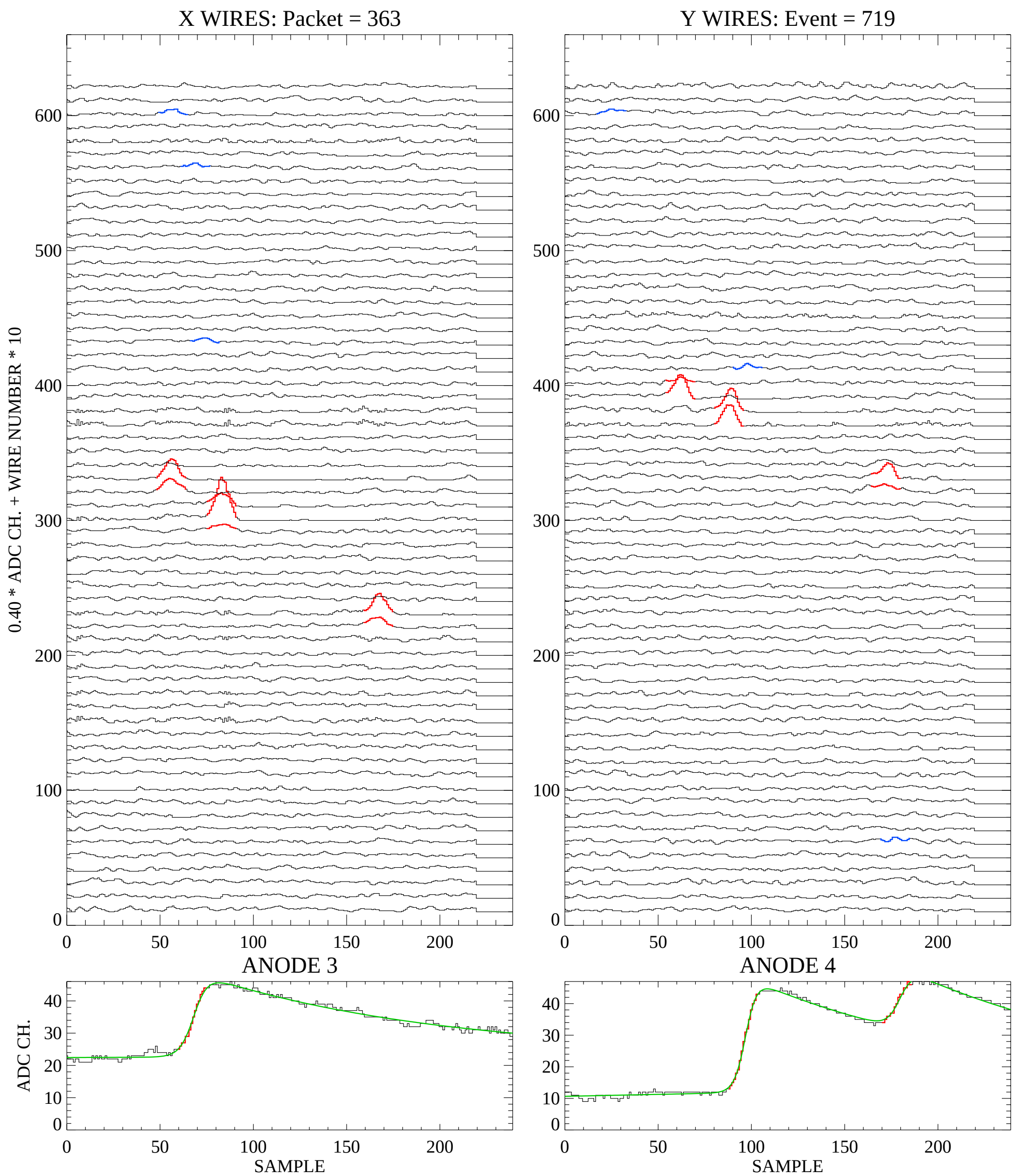
- Multiple interaction events typical at these energies are clearly identified and used to image the source position and its energy via Compton kinematics.



Signal Recognition and Event Reconstruction

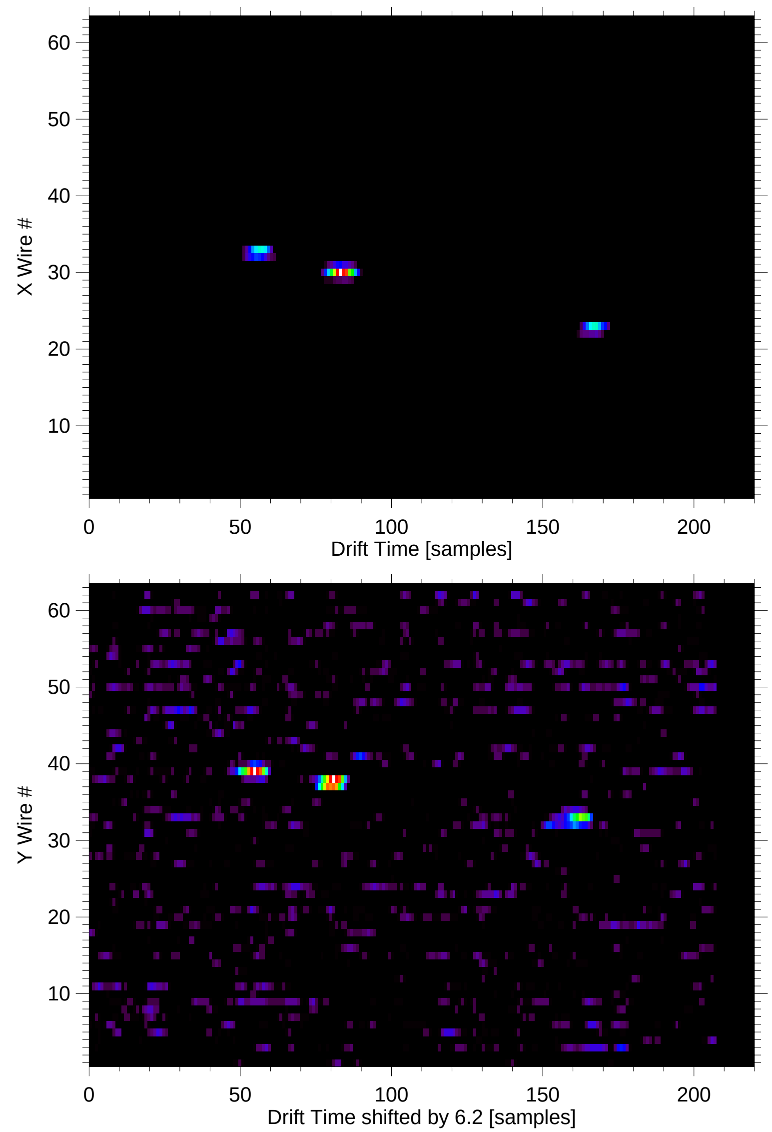
X-/Y-Wire and Anode Signals vs. Drifttime

γ-ray with three interactions in the detector.

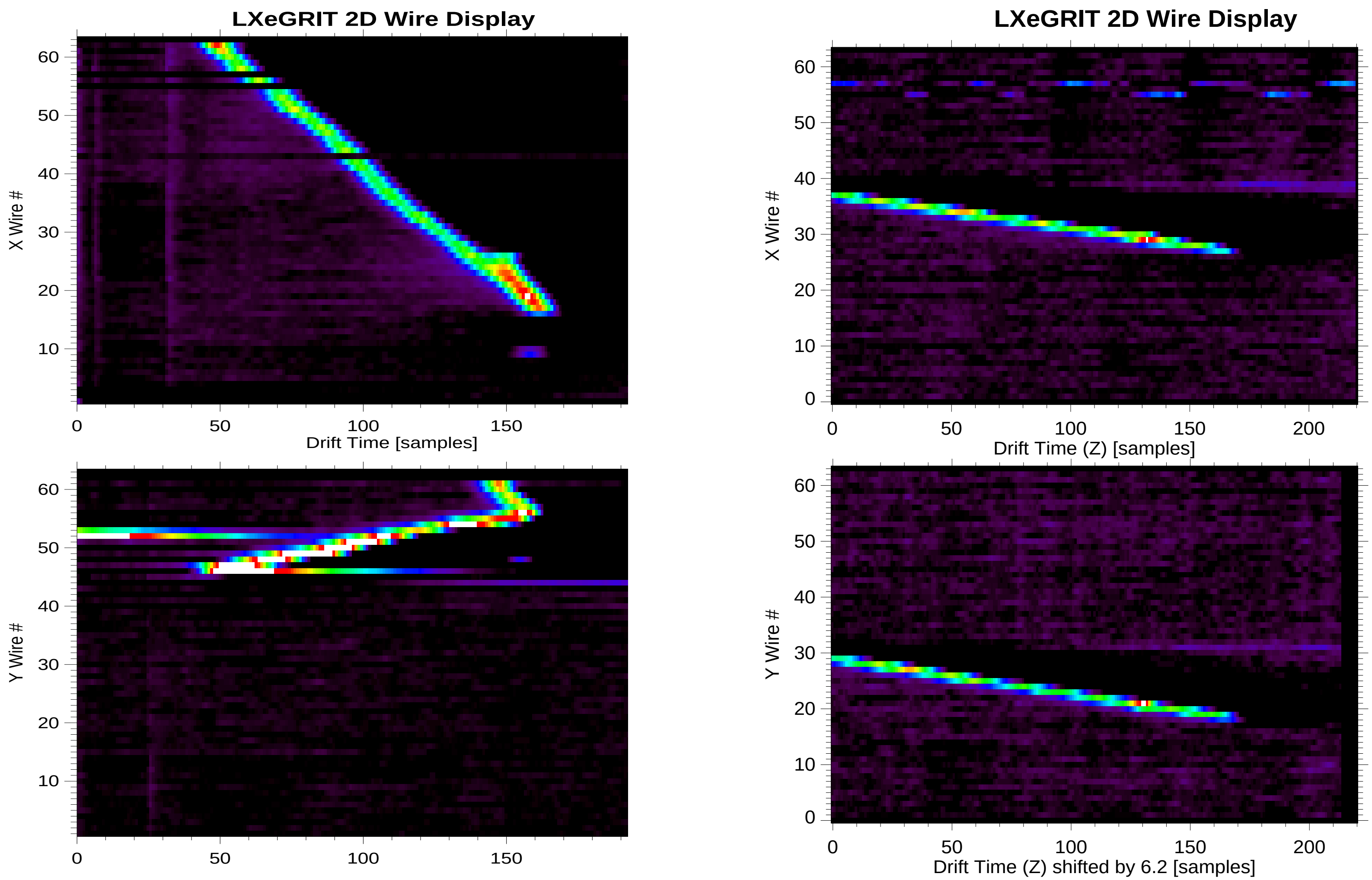


False Color Display of X-/Y-Wire Signals

(same event)

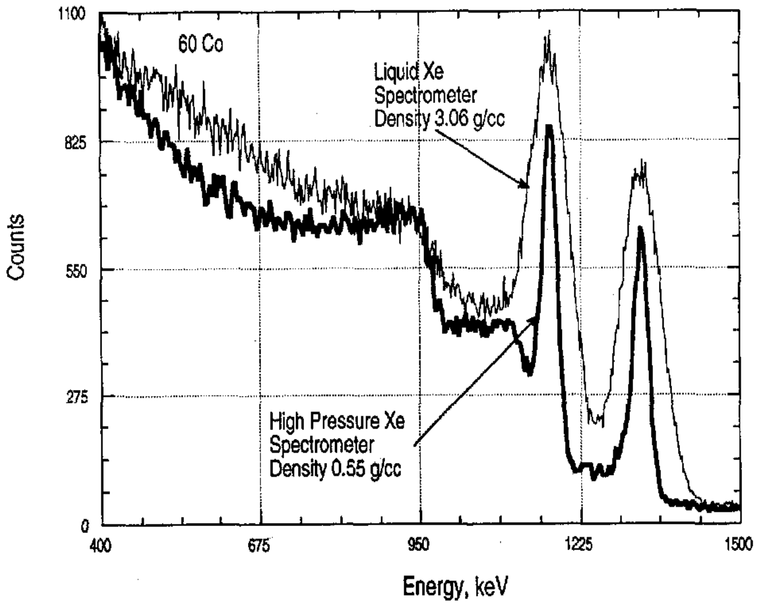


Tracking with a TPC:
LXeGRIT May 7 1999 - Flight Data - Charged Particle Tracks



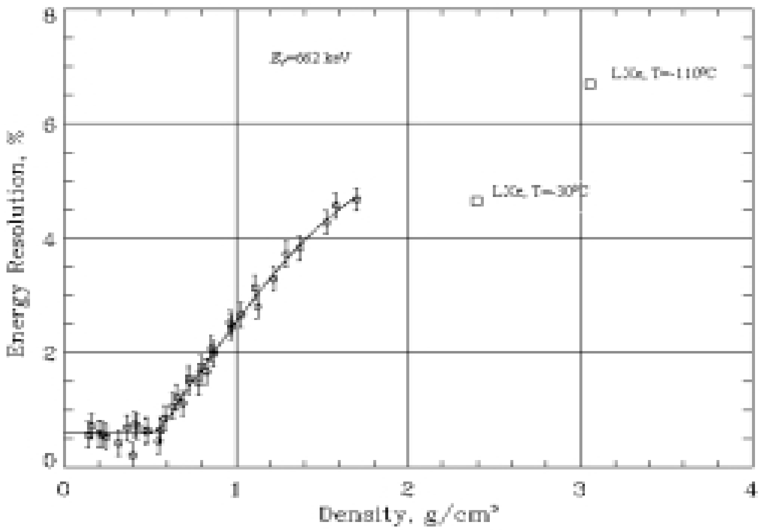
Improving Energy Resolution: from LXe to HPXe

^{60}Co spectrum in LXe and HPXe



- the measured energy resolution achieved in LXe (5 % FWHM at 1 MeV) is far from the Fano limit (0.2 % FWHM at 1 MeV)
- the measured energy resolution in HPXe (0.5 % FWHM at 1 MeV), for density $\leq$ 0.55 g$\cdot$cm^{-3}, approaches the statistical limit
- several groups, including the Columbia one, have studied the resolution response in HPXe

Energy Resolution vs. Density in HPXe

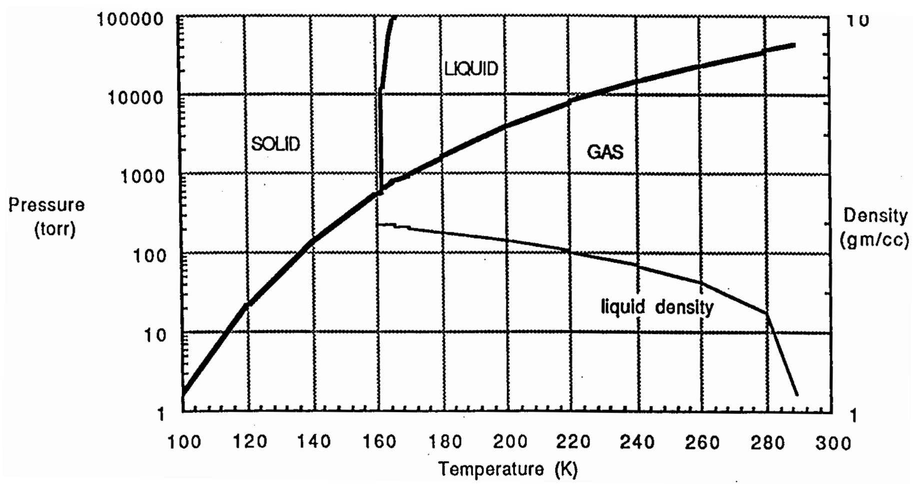


Bolotnikov and Ramsey, 1997

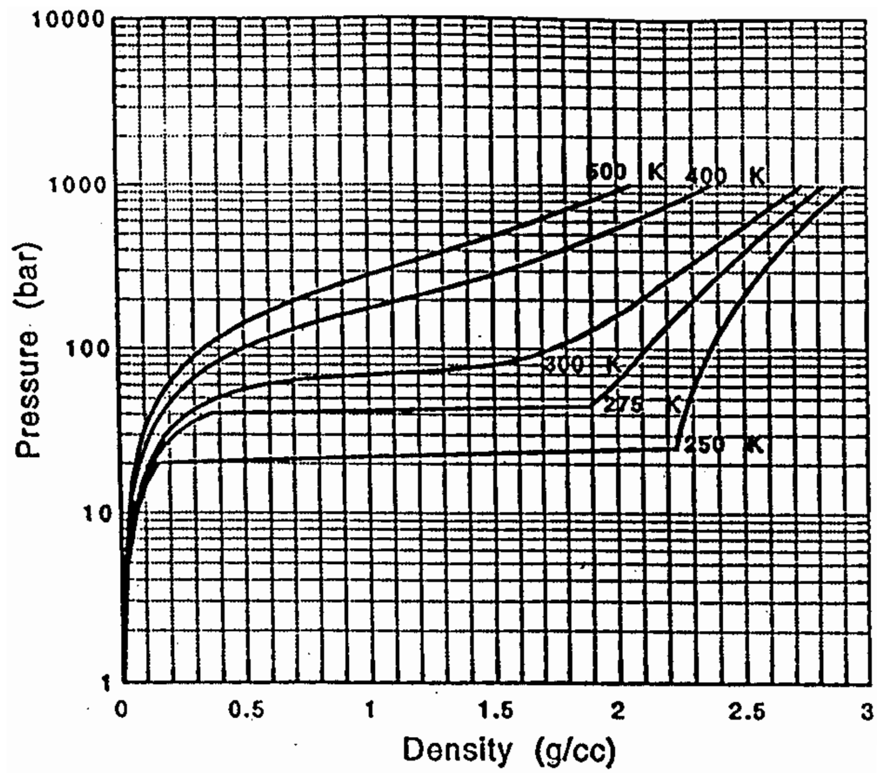
- above 0.55 g$\cdot$cm^{-3} the resolution starts to degrade approaching the value in LXe
- 0.55 g$\cdot$cm^{-3} is close to the critical point of Xe (p_c=57.6 atm, T_c=289.7 K, ρ_c=1.1 g$\cdot$cm^{-3}) where Xe is far from ideal gas
- the degradation of resolution appears correlated to density fluctuations in dense Xe and the appearence of the first exciton band

Xenon Phase Diagram

Pressure vs. Temperature



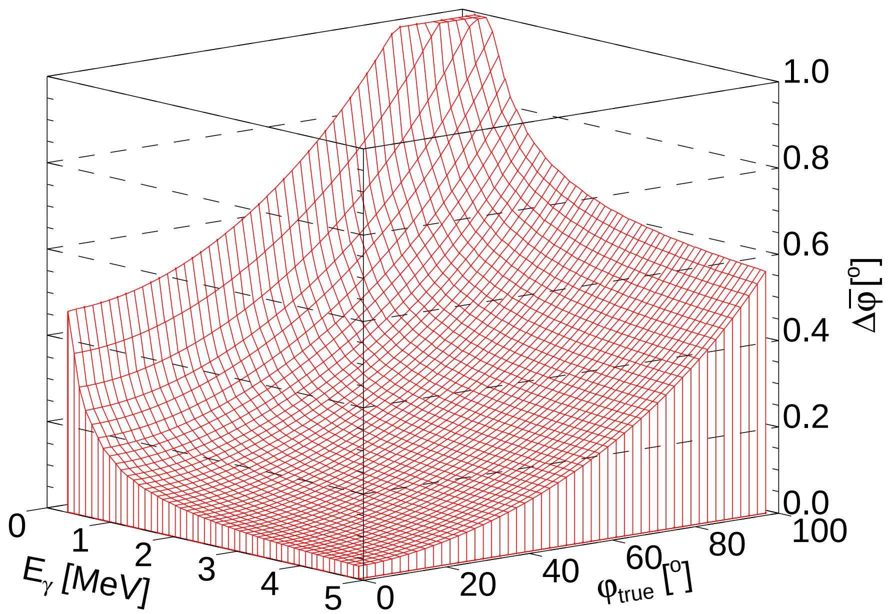
Pressure vs. Density

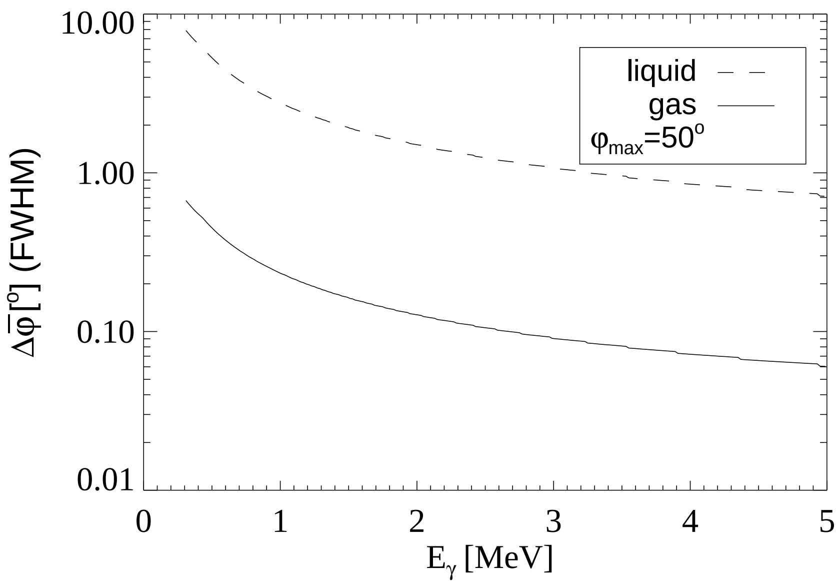


Contribution of the Energy Resolution to the Angular Resolution of a Compton Telescope

Excellent energy resolution → better angular resolution → lower background → improved sensitivity but.. only for narrow line point sources.

To maintain sensitivity to broad lines and spatially extended sources → background reduction schemes independent of any particular source property → i.e. 3D event imaging and electron tracking



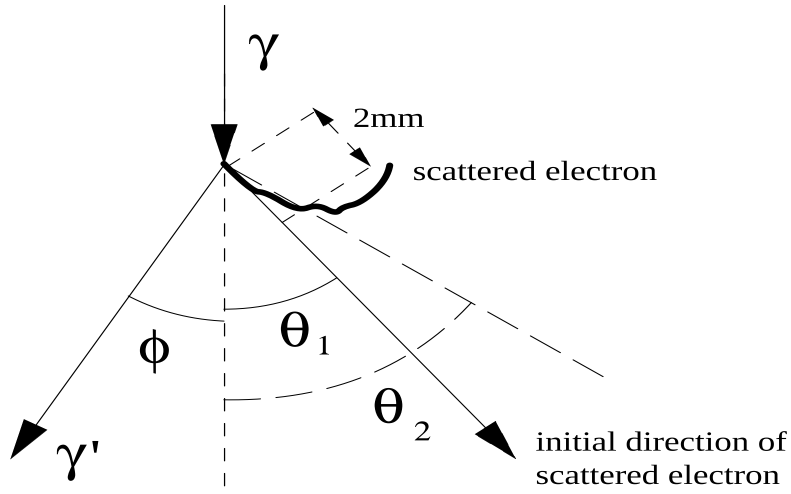


- 5 keV (FWHM) at 1 MeV Energy Resolution in Converter and Calorimeter

- 1 mm Position Resolution in Converter and Calorimeter

Tracking the Compton Recoil Electron

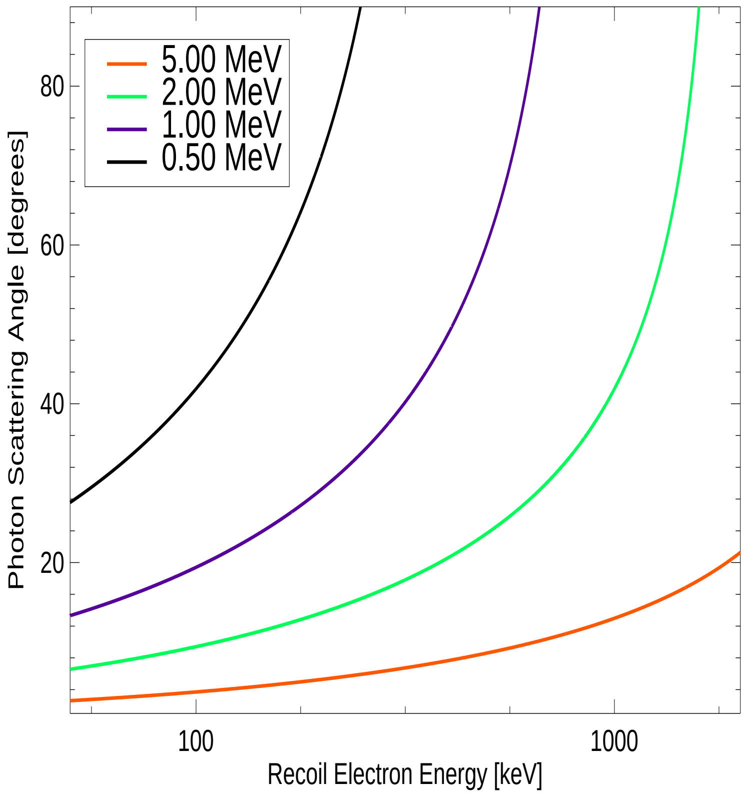
- Ultimate goal of a Next (3^{rd}?) Generation Compton Telescope: a precise measurement of the Compton electron direction, in addition to the gamma-ray scattering angle, completely constrains the kinematics of the scattering.
- The 360^o event circle is reduced to an arc with opening angle $\sim$ uncertainty on the projected electron scattering angle.
- The imaging performance and especially the S/N is improved. Every "bit" of information on the electron momentum will be valuable for background suppression and thus will improve sensitivity.
- For gamma-rays from nuclear lines, Compton recoil e^- have energies well below 1 MeV. Overall increase in instrument complexity to include e^- track measurement needs to be carefully weighted with the overall improvement in performance.



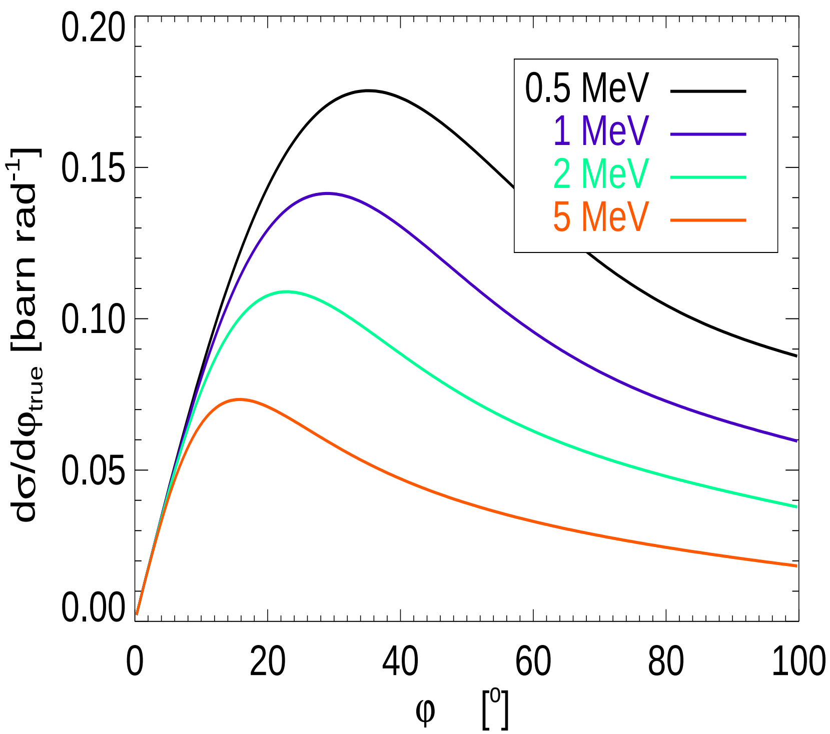
- A great experimental challenge due to the short range, distorted by large Coulomb scattering, of the low energy e^- associated with Compton interactions of MeV photons.
- Best approach for this measurement: a very low density and low Z detector, with very fine granularity. Good candidates are gas TPC or Si strips. While hard to achieve, tracking low energy e^- is of considerable interest not only for Compton telescopes. Experiments which share the same challenge include: (a) ν_e e elastic scattering to detect low energy solar neutrinos and (b) $\bar{\nu}_e$ e elastic scattering to measure the $\bar{\nu}_e$ magnetic moment.

Compton Cross Section and Scattering Kinematics (I)

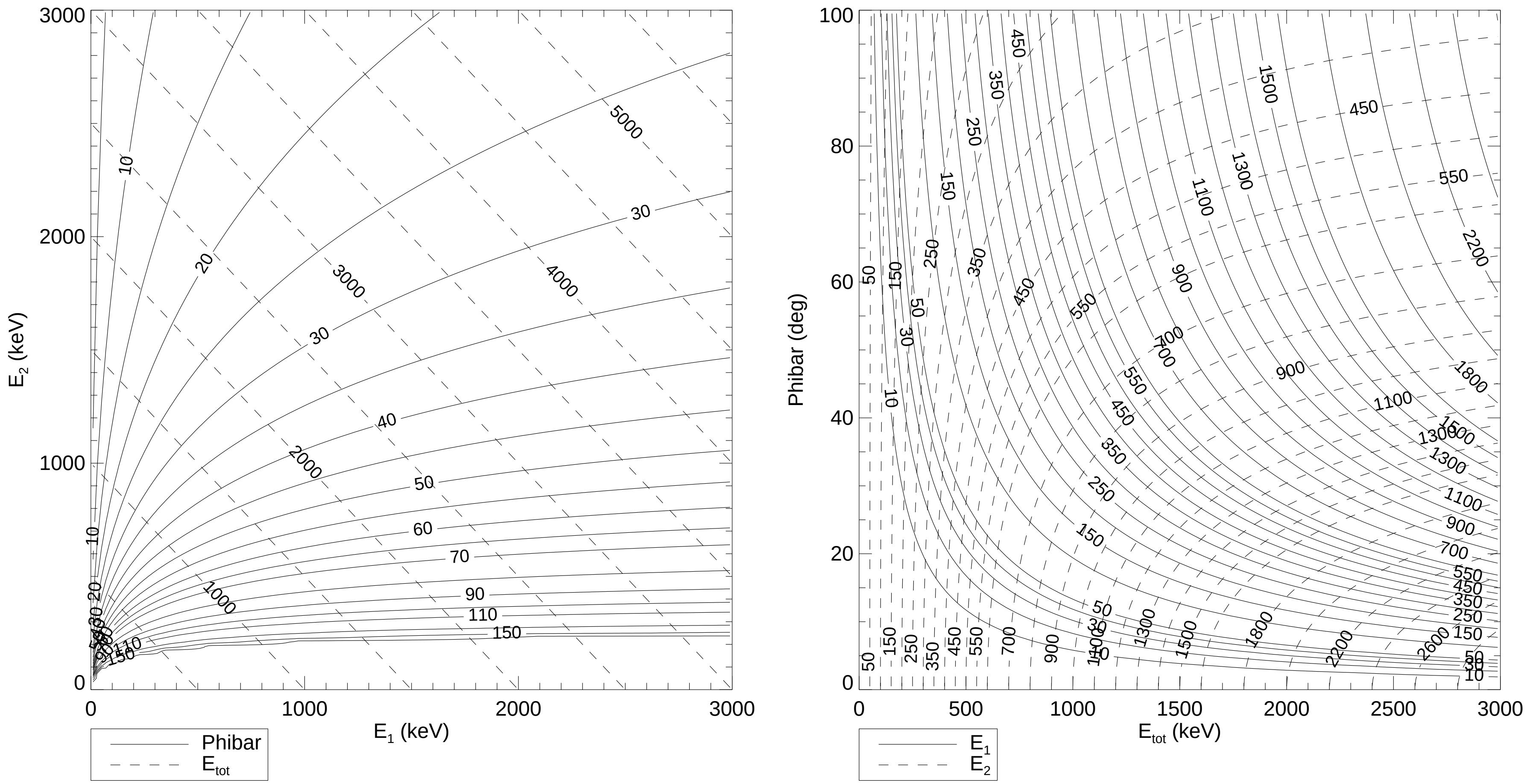
Photon Scattering Angle vs. Electron Energy



Cross Section vs. Photon Scattering Angle

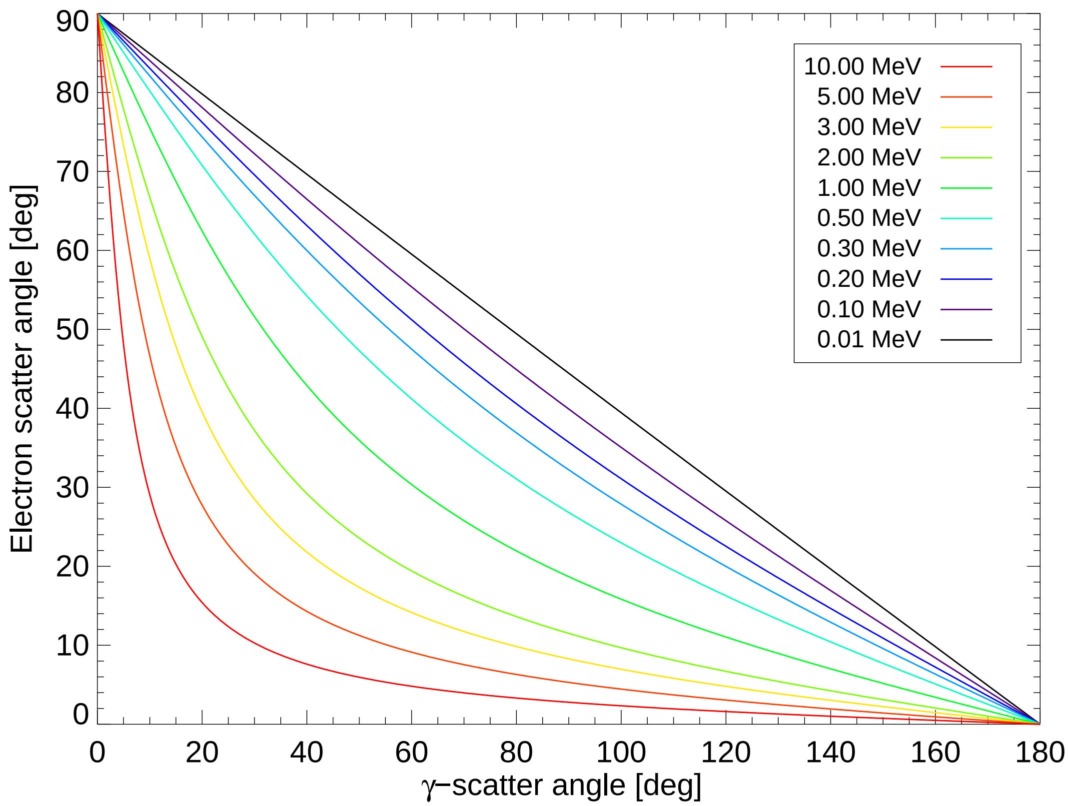


Compton Scattering Kinematics (II)

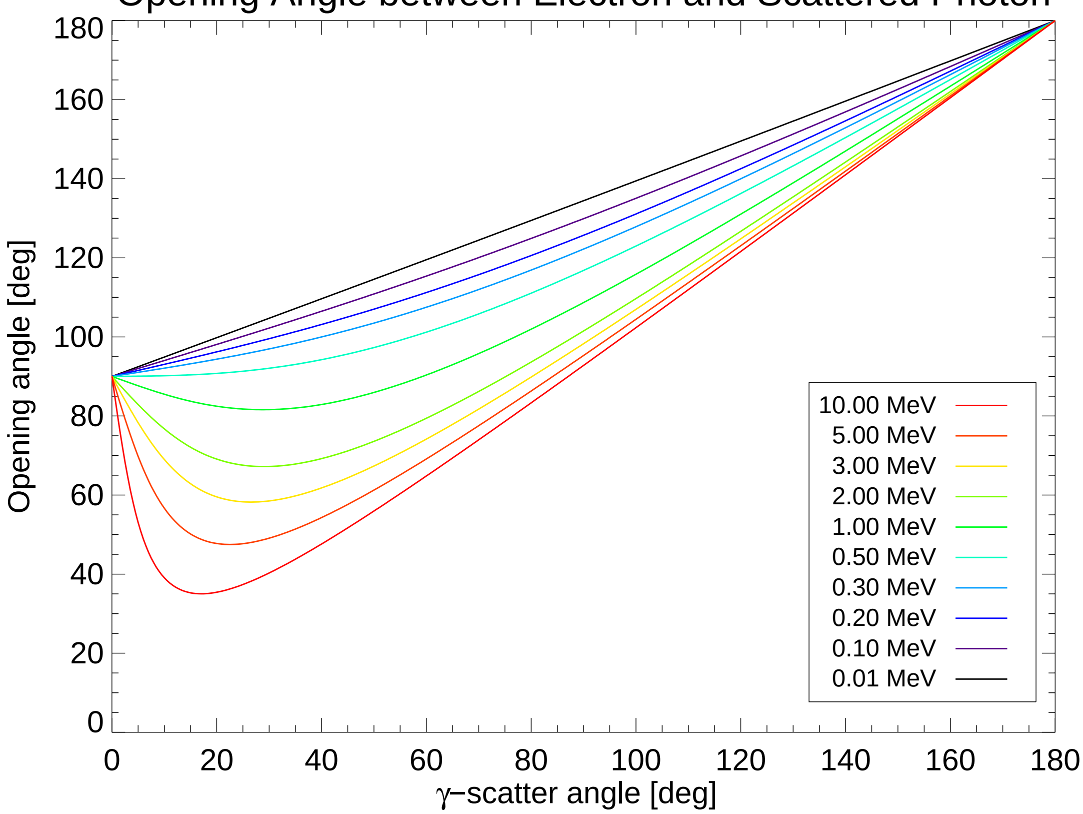


Compton Scattering Kinematics (III)

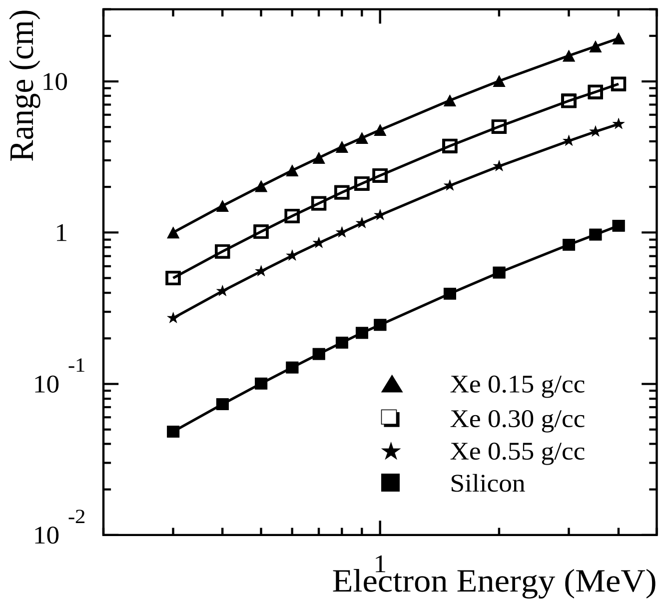
Electron vs. Photon Scatter Angle

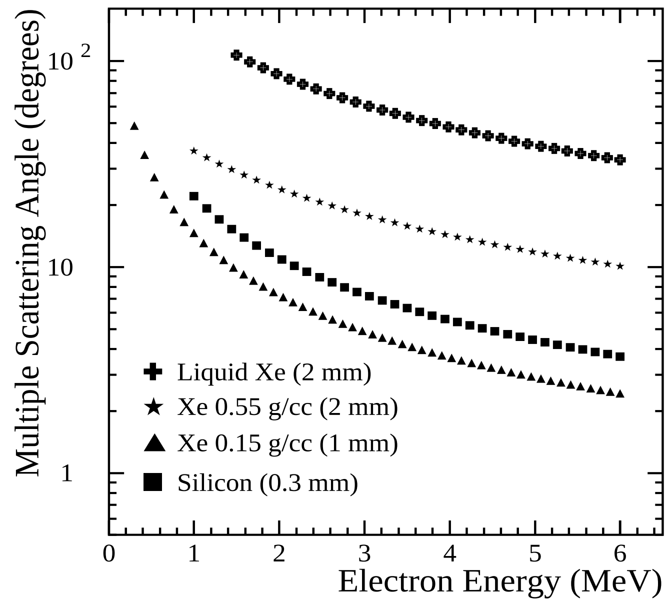


Opening Angle between Electron and Scattered Photon



Electron Range and Multiple Scattering for Xenon and Si

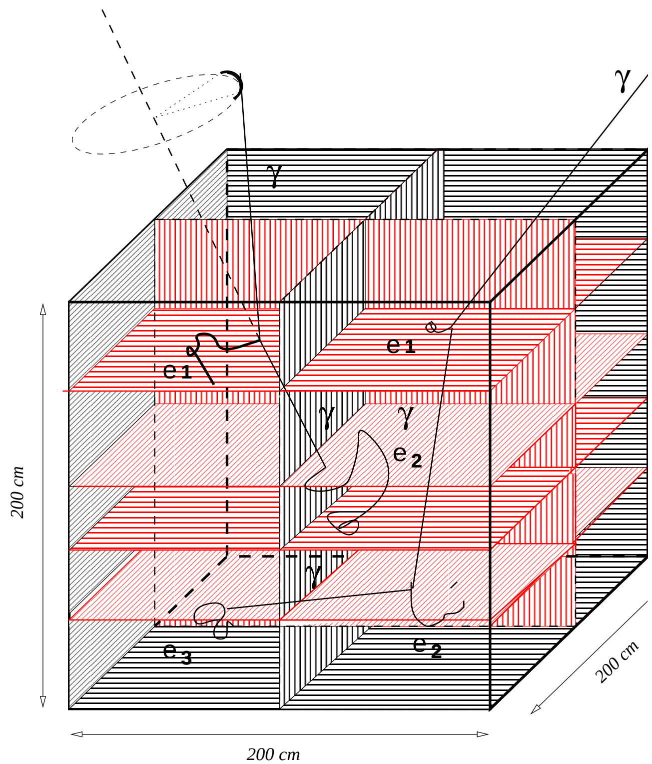




range of 1 MeV e^-: from a few mm (Si) to a few cm (low density gas)

multiple scattering error large: only the first few mm of track useful, requiring very fine detector granularity

Xe – ACT:
Low Density (0.15 g$\cdot$cm^{-3}) Xe TPC Version

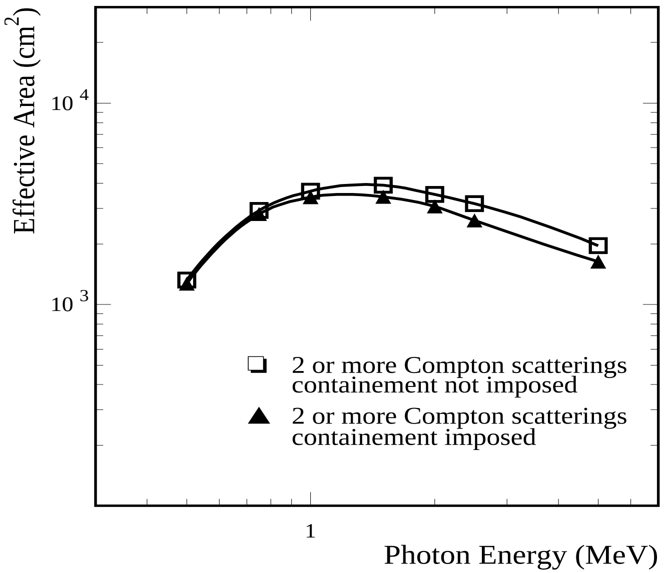


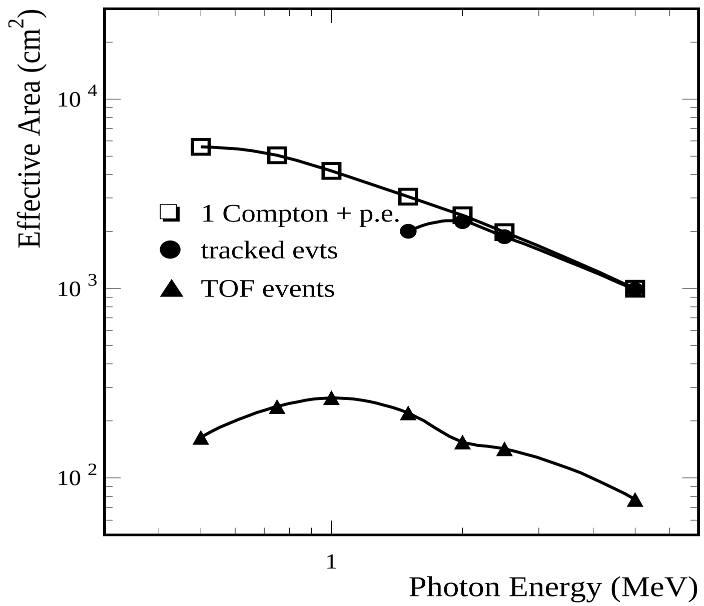
Instrument Characteristics	
Energy range (Compton imaging)	0.3 – 10 MeV
(extendable using pair production events)	10 – 100 MeV
Energy resolution (FWHM)	5 keV @ 1 MeV
Position resolution (1 σ)	0.3 mm (3 dimensions)
Angular resolution (1 σ)	8 arcmin at 2 MeV
Field-of-view	$\sim 2\pi$
Effective area at (0.8 – 2 MeV)	~ 6000 cm^2
Sensitivity (3 σ, $t_{obs} = 10^6$ s)	
Narrow line source ($\lesssim$ 5 keV)	$\sim 1\times10^{-7}\ \gamma cm^{-2} s^{-1}$
Broadened line source (30 – 40 keV)	$\sim 3\times10^{-7}\ \gamma cm^{-2} s^{-1}$
Continuum (1 – 3 MeV)	$\sim 1\times10^{-6}\ \gamma cm^{-2} s^{-1} MeV^{-1}$
Compton Telescope Configuration	
Event imaging technique	Time projection chamber
Background rejection: 3D event imaging and Compton electron tracking	Factor > 100 improvement over COMPTEL
Instrument volume	$2\times2\times2$ m^3

Low Density (0.15 $g \cdot cm^{-3}$) Option:
A $2 \times 2 \times 2$ m^3 Sensitive Volume TPC

MC Estimation of the Effective Area for Compton Events Only

PHOTONS AT NORMAL INCIDENCE



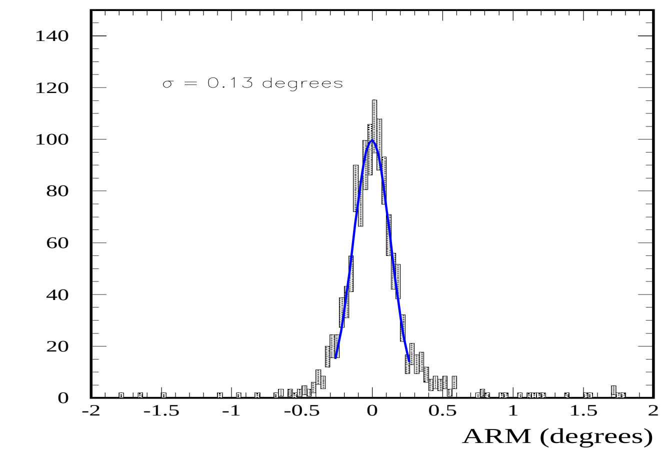


- Granularity: 1 mm
- Energy Threshold: 100 keV
- Minimum Energy for e^- Tracking: 1 MeV
- Minimum Separation between 1st and 2nd Scattering: 10 cm
- Minimum Separation between 1st and 2nd Scattering for TOF: 100 cm

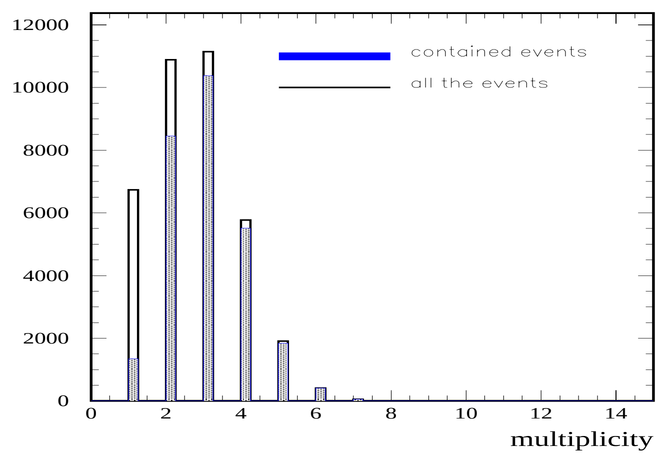
Event Categories:

- 1 Compton scattering + p.e.
- $\geq$ 2 Compton scatterings + p.e.
- $\geq$ 3 Compton scatterings
  (energy containment not required)

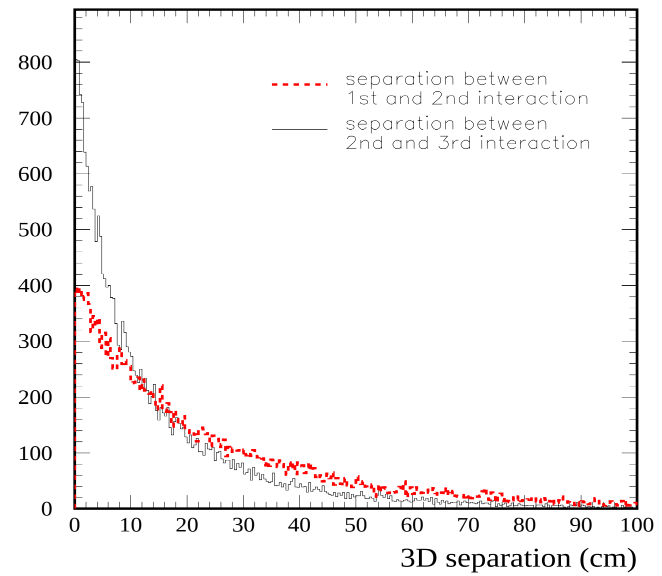
Low Density (0.15 g·cm^{-3}) XeTPC



ARM distribution for 2 MeV photons.



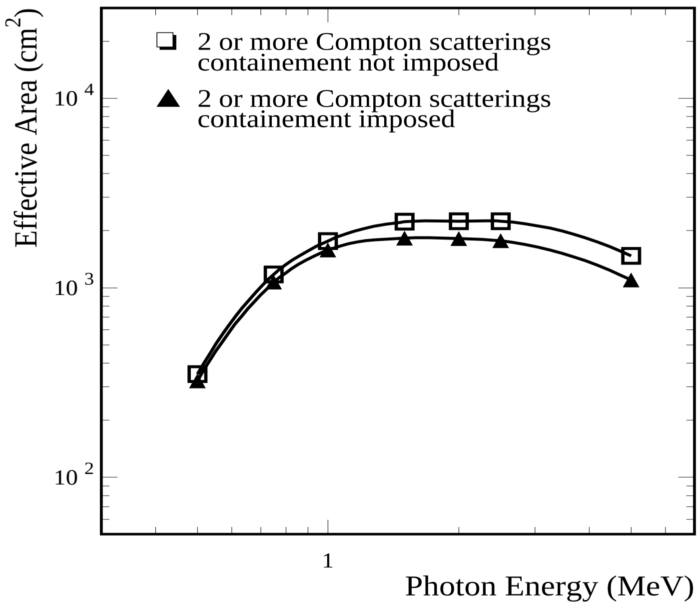
Number of interactions in the active volume (multiplicity). Incoming photon energy is 2 MeV. Normal Incidence. Energy containment not required.



Spatial separation between 1st and the 2nd interaction (red) and between 2nd and 3nd interaction (black) events with multiplicity ≥ 3. Incoming photon energy is 2 MeV. Normal Incidence.

High Density (0.55 g·cm^{-3}) Option:
A $1.2 \times 1.2 \times 1.2$ m^3 Sensitive Volume TPC

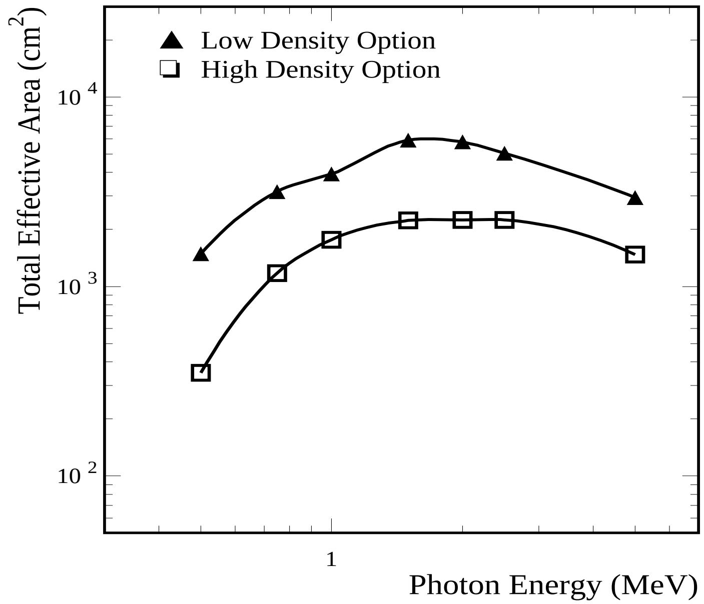
Monte Carlo Effective Area
Events with 2 or more Compton



Event Categories:

- 1 Compton scattering + p.e. not considered
- $\geq$ 2 Compton scatterings + p.e.
- $\geq$ 3 Compton scatterings (energy containment not required)

Comparison of the two Options



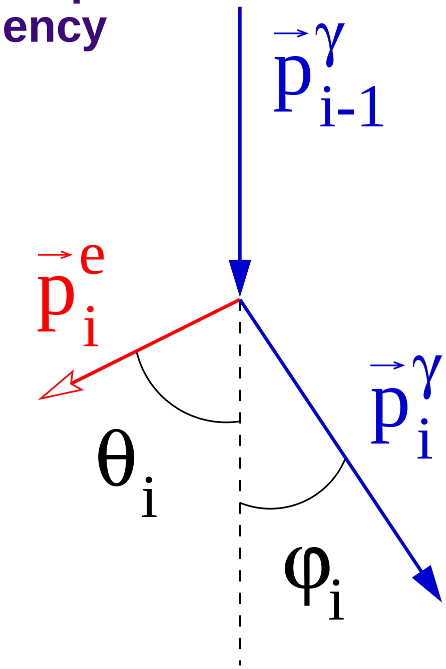
LOW DENSITY:

- Effective Area ($\sim$ 1.5 MeV) $\sim$ 6000 cm^2
- Efficiency ($\sim$ 1.5 MeV) $\sim$ 15%
- Tracking Capability

HIGH DENSITY:

- Effective Area ($\sim$ 1.5 MeV) $\sim$ 2000 cm^2
- Efficiency ($\sim$ 1.5 MeV) $\sim$ 14%
- More Compact Structure

Reconstructing the Sequence of Multiple Compton Interactions: An Essential Step for Efficiency



Energy and momentum conservation in Compton scattering yield two independent equations for the photon scatter angle φ_i and the electron scatter angle θ_i $(i = 1, \ldots, N-1)$:

$$1 - \cos\varphi_i = \frac{m_0c^2}{E_i^\gamma} - \frac{m_0c^2}{E_{i-1}^\gamma} \qquad (1)$$

$$\cot\theta_i = \left(1 + \frac{E_{i-1}^\gamma}{m_0c^2}\right) \tan\frac{\varphi_i}{2} \qquad (2)$$

Consider an event with N energy deposits $E_i (\approx E_i^e)$ at N locations $\vec{x}_i$ in the sensitive volume. For a given sequence, the measured $\vec{x}_i$ determine geometrically $N-2$ scatter angles $\varphi_i^{\triangleleft}$ $(i = 2, \ldots, N-1)$. On the other hand, the measured E_i give $N-1$ Compton scatter angles $\bar{\varphi}_i$, according to equation (1), noting that $E_i^\gamma = \sum_{j=i+1}^{N} E_j$ $(i = 0, \ldots, N-1)$. This redundant information allows to test the sequence of the interaction points based solely on kinematics. In Aprile et al. 1993, we used such approach to compute a test statistic and apply this for the case of known source position (φ_1) and line energy (E_0^γ). For pairs of interactions i and $i+1$ we have:

$$W_{i-1}W_i = \frac{W_{i-1} - W_i}{1 - \cos\varphi_i} = \frac{E_i}{1 - \cos\varphi_i} \qquad (i = 1, \ldots, N-1) \qquad (3)$$

$$W_iW_{i+1} = \frac{E_{i+1}}{1 - \cos\varphi_{i+1}} \qquad (i = 0, \ldots, N-2) \qquad (4)$$

where $W_i = E_i^\gamma / m_0 c^2$ designates the measurement of E_i^γ by a combination of the geometrically measured angles $\varphi_i^\triangleleft$ and $\varphi_{i+1}^\triangleleft$ as well as the energy deposits E_i and E_{i+1}. Subtracting above equations from each other yields:

$$W_i = \frac{E_i}{E_i + E_{i+1}} \frac{1}{1 - \cos\varphi_i} - \frac{E_{i+1}}{E_i + E_{i+1}} \frac{1}{1 - \cos\varphi_{i+1}} \qquad (i = 1, \ldots, N-2) \tag{5}$$

On the other hand, from energy conservation alone, we have $W_i' = \sum_{j=i+1}^{N} E_j \ (i = 0, \ldots, N-1)$.
To test the validity of the assumption that the total energy of the incoming photon is contained as well as if the assumed initial direction is kinematically possible, the following test statistic is thus constructed:

$$T_W = \sum_{i=0}^{N-2} (W_i - W_i')^2 \tag{6}$$

Ideally, T_W is zero for the correct sequence, if the photon is fully contained. With measurement errors, T_W is always greater than zero, but the correct sequence still produces the minimum value. At least $N = 3$ interactions are required for the Compton sequence reconstruction in the general case. For these multiple Compton events, it is also clear from the above kinematics equations that if one knows the interactions sequence, the measured energy deposits in the first and second scattering and the scatter angle from the measured first three locations $\vec{x}_i$, can be used to infer the incoming photon energy, as suggested by Kurfess et al.:

$$E_0^\gamma = E_1 + \frac{E_2}{2} \left(1 + \sqrt{1 + \frac{4 \cdot m_0 c^2}{E_2 \cdot (1 - \cos\varphi_2)}} \right) \tag{7}$$

For events with $N = 2$ interactions, there is no unique solution to the incoming photon direction unless one can rely on a TOF measurement or a tracked scattered Compton electron direction.

Summary

- A Xenon Time Projection Chamber with 3D event imaging (submillimeter quality), Compton electrons tracking and excellent energy resolution (for gas density $\leq$ 0.55 g·cm$^-3$) can meet the observational requirements of a future nuclear line astrophysics mission with 50 $\geq$ times more sensitivity than CGRO and INTEGRAL.

- With a 2 m^3 sensitive volume filled with Xe gas between 20-30 atm, Monte Carlo simulations show that for normal photon incidence, the effective area for multiple Compton interactions is about 6000 cm^2 @ 1 MeV. Higher density allows a more compact geometry, at the expense however of electron tracking capability. When combined with the excellent background rejection capabilities of a TPC with full event imaging in one homogeneous volume, enhanced by tracking and possible TOF measurement with the fast Xe light, such effective area translates into a line sensitivity well beyond the $10^{-7}\gamma\cdot\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$ level.

- The experience at Columbia on this type of detector for a Compton telescope and the important feedback from the LXeGRIT ballon flight data, will permit us to advance with this new development under the current SR&T program, guided as well by Monte Carlo studies and studies with TPCs for other physics applications. There are nevertheless new technical challenges which one faces in going from liquid to gas phase. More stringent requirements are placed on construction materials choice (the room temperature operation has a price), on low noise charge readout electronics, on more efficient light readout, etc. New measurements are needed to find the optimum operating conditions for best detector response not only in energy resolution, but also spatial and time resolutions.